

# Breeding for high-density planting and yield stability of newly developed maize hybrids across arid agro-environments

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## ABSTRACT

High planting density is a key strategy for increasing maize (*Zea mays* L.) productivity. Therefore, this study evaluated 17 newly developed yellow maize single-cross hybrids under three planting densities (59 524, 71 429, and 89 286 plants ha<sup>-1</sup>). The hybrids were evaluated at two contrasting locations in Sakha in the Nile Delta and Sids in Middle Egypt. Earliness, vegetative traits, ear morphology, and grain yield were recorded at both locations. Combined ANOVA revealed highly significant effects ( $p < 0.01$ ) of location, planting density, hybrids, and all interactions for most traits. This indicates strong environmental sensitivity and wide genetic variability. Increasing planting density enhanced grain yield by approximately 12.15% at Sakha (from 9.71 to 10.89 t ha<sup>-1</sup>) and 15.97% at Sids (from 8.39 to 9.73 t ha<sup>-1</sup>). Otherwise, increasing planting density reduced ear leaf area (5.87% at Sakha and 11.15% at Sids), number of rows per ear (3.91% at Sakha and 6.83% at Sids), and number of kernels per row (7.34% at Sakha and 10.01% at Sids), while grain yield increased at both locations. This confirms that higher number of plants per unit area compensated for the per plant reduction in ear traits. The assessed maize hybrids exhibited highly significant genetic variation for earliness, vegetative growth, and yield-related traits. The hybrids, Hib-6, Hib-11, Hib-7, Hib-16, and Hib-17 produced yields up to 13.6 t ha<sup>-1</sup> and maintained stable performance across environments. Hib-6 exhibited the highest mean productivity (12.66 t ha<sup>-1</sup> at Sakha and 10.46 t ha<sup>-1</sup> at Sids) and the highest stress tolerance index (1.75 and 1.18, respectively), indicating strong adaptation to high-density stress. Multivariate analyses, including cluster analysis, heatmap classification, AMMI, GGE biplot, and tolerance indices, effectively summarized the complex data structure. These analyses distinguished broadly adapted, high-performing hybrids from poorly adapted hybrids. The obtained results demonstrated that breeding for yield potential and tolerance to high planting density is feasible and provides a set of promising hybrids.

**Key words:** AMMI biplot, arid environments, cluster analysis, density tolerance indices, genetic high-density tolerance, genotype by environment interaction, GGE biplot, intensive cultivation, yellow maize, *Zea mays*.

## INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide (Adugna, 2025). It provides a major source of calories, protein, and industrial raw material for both humans and livestock (Li et al., 2025). Yellow maize has a vital role in the poultry and livestock feed industries. Moreover, it is increasingly demanded by the

starch and bio-ethanol sectors (Niu et al., 2023). Therefore, increasing maize production is a globally strategic goal. It is cultivated on approximately 208.23 million hectares worldwide with an annual production of 1241.56 million tons (FAOSTAT, 2025). In Egypt, it is cultivated on 950 thousand hectares and produces around 7.13 million tons annually.

Expansion of maize cultivated area is constrained by limited arable land and competition with strategic crops. Therefore, intensification through improved agronomic practices and superior genotypes is essential for increasing maize production. Among intensification strategies, increasing plant population is one of the most effective and widely adopted tools (Haarhoff and Swanepoel, 2018). It enhances the exploitation of available soil resources. Nevertheless, high planting density intensifies intra-specific competition for light, water, and nutrients. It also could increase lodging and accelerate maturity in particular under heat or moisture stress (Cui et al., 2022). Therefore, it is critical to breed maize hybrids to tolerate high-density stress. Density-tolerant hybrids are characterized by more erect leaves, optimal ear placement, and balanced root and shoot relations (Jafari et al., 2024). Also, these hybrids should possess the capacity to maintain adequate ear size and kernel number under competition (Ygzaw et al., 2025). Developing such hybrids has become a priority in maize breeding programs targeting resource-limited environments.

Density-tolerance is strongly affected by environmental conditions and genotype-by-environment interaction (GEI) (Yue et al., 2025). Climatic variables further contribute significantly to shaping GEI patterns and determining hybrid performance across environments (Pavlov et al., 2024). In Egypt, maize is commonly grown during the hot, dry summer. The soils vary widely in texture, fertility, and organic matter content between locations. Maize seasons are characterized by high temperatures during flowering and grain filling, occasional water shortages, and variable soil conditions. These conditions can interact with planting density to adjust plant architecture, reproductive success, and grain yield (Djaman et al., 2022). Therefore, the hybrids which perform well at a site or density could not maintain their superiority under different agro-environmental conditions. Consequently, understanding GEI under contrasting locations and plant populations is essential for identifying broadly adapted high-density-tolerant hybrids (Zhu et al., 2023).

Multivariate statistical tools offer a comprehensive framework for exploring adaptation patterns. Integrative approaches that combine additive main effects and multiplicative interaction (AMMI), Genotype plus Genotype by Environment (GGE) biplot, and other stability metrics provide effective evaluation of hybrid adaptability across diverse environments (Priyanto et al., 2024). Hierarchical clustering can group hybrids based on their similarity in agronomic performance (Sinana et al., 2023). Heatmap visualization combines clustering with color scale to identify well and poor hybrids across environments (Du and Pechlivanidis, 2025). Density tolerance indices provide a quantitative framework for evaluating hybrid performance under contrasting planting densities (Tang et al., 2018). These indices have demonstrated effectiveness in dissecting genotypic responses to specific competition. This enables precise identification of genotypes that maintain yield stability under high-density stress. The GGE interaction model facilitates graphical interpretation of GEI (Ma et al., 2024). The GGE presents the stability of assessed hybrids and the characterization of the discriminating ability of test environments. The AMMI effectively partitions GEI into genotype and environment main effects plus a multiplicative residual (Barati et al., 2025). The AMMI visualizes hybrid performance across environments and enables precise dissection of stability and specific adaptation patterns. Integrating these approaches in multi-environment trials provides a powerful tool for maize breeding to develop hybrids for intensive high-density systems.

In the present study, six diverse yellow maize inbred lines were used to generate newly developed single-cross hybrids. These inbred lines were collected from international and national breeding programs and pre-selected for their adaptive traits under high planting density. The developed hybrids were evaluated at two contrasting locations in Sakha in the Nile Delta and Sids in Middle Egypt. At each location the hybrids were evaluated under three planting densities representing low, intermediate, and high plant populations. This study aimed to contribute to the development of maize hybrids that can sustain high yield under intensive cultivation. Specifically, the objectives were: (i) To explore the effects of location, planting density, and genotype, and their interactions, on earliness, vegetative growth, ear traits, and grain yield; (ii) to identify high-yielding, density-tolerant hybrids suitable for commercial cultivation and breeding programs; and (iii) to apply multivariate procedures, including hierarchical clustering, heatmap analysis, AMMI and GGE biplot, to study hybrids performance and adaptation across environments.

## MATERIALS AND METHODS

### Plant material

Six diverse yellow maize (*Zea mays* L.) inbred lines were utilized in this study. Four inbreds were obtained from Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), Mexico, one from the Agricultural Research Center in Egypt, and one from the International Institute of Tropical Agriculture (IITA) in Nigeria (Table 1). These inbred lines were selected through preliminary screening trials for their adaptive traits under high planting density conditions. The inbred lines were sown during the summer season of 2021 at the Experimental Stations of the Agricultural Research Center (30°01'17" N, 31°12'34" E), Egypt. The inbreds were sown on two sowing dates to produce sufficient hybrid seeds (17 May and 1<sup>st</sup> June). Before the first irrigation, plants were thinned to one per hill. At flowering, all possible cross combinations among the six inbred lines were conducted following a half-diallel mating design (without reciprocals), resulting in 15 F<sub>1</sub> hybrids.

**Table 1.** Name, pedigree, and origin of the genotypes used in this study.

Code	Genotype	Pedigree	Source
G58	Gz-658	Cargill 922	CIMMYT
G04	Gm-1004	Sub-tropical yellow maize (DMR) imported from IITA	Nigeria
G21	Gm-1021	Sd.121 × Pop. (DMR-ESR) Yellow	Egypt
L44	L044-171	EXP 9281	CIMMYT
L74	L074-213	CP × 888	CIMMYT
L78	L078-33	NS × 9002	CIMMYT
Hib-1	G58×G04	Gz-658 × Gm-1004	Newly developed
Hib-2	G58×G21	Gz-658 × Gm-1021	Newly developed
Hib-3	G58×L44	Gz-658 × L044-171	Newly developed
Hib-4	G58×L74	Gz-658 × L074-213	Newly developed
Hib-5	G58×L78	Gz-658 × L078-33	Newly developed
Hib-6	G04×G21	Gm-1004 × G21	Newly developed
Hib-7	G04×L44	Gm-1004 × L44	Newly developed
Hib-8	G04×L74	Gm-1004 × L74	Newly developed
Hib-9	G04×L78	Gm-1004 × L78	Newly developed
Hib-10	G21×L44	Gm-1021 × L44	Newly developed
Hib-11	G21×L74	Gm-1021 × L74	Newly developed
Hib-12	G21×L78	Gm-1021 × L78	Newly developed
Hib-13	L44×L74	L044-171 × L74	Newly developed
Hib-14	L44×L78	L044-171 × L78	Newly developed
Hib-15	L74×L78	L074-213 × L78	Newly developed
Hib-16	SC162	Gz653 × Gz639	Egypt
Hib-17	SC168	Gz649 × Gz668	Egypt

### Experimental sites

The field experiment was conducted during the summer of 2022 at two locations. The developed hybrids were evaluated at two contrasting locations in Sakha in the Nile Delta and Sids in Middle Egypt. The tested locations were Sakha Research Station, Kafr El Sheikh (31°09'34" N, 30°94'46" E) and Sids Research Station, Bani Sweif (28°95'91" N, 30°94'49" E). The soils at the two experimental sites are classified as clay-textured. Sakha had higher clay content (60.04%) compared to Sids (52.31%). While the sand was higher in Sids (17.24%) than in Sakha (9.72%). Both soils are slightly alkaline with pH values around 7.85 to 7.93. Moreover, Sakha had significantly greater organic matter content (11.7%) than Sids (1.33%). The climate of two sites was characterized as hot and dry during the maize growing season, with high temperatures, low humidity, and

negligible summer rainfall (Table 2). Extreme temperature and humidity conditions can adversely affect pollen viability and fertilization, and accordingly reduce successful kernel set. Therefore, the parental inbred lines used in this study were previously evaluated and adapted to the regional climatic conditions.

**Table 2.** Monthly average minimum temperature, maximum temperature, humidity and precipitation during the two growing seasons at two experimental sites.

Month	Minimum temperature °C	Maximum temperature °C	Humidity %	Precipitation mm
Sakha 2022				
May	16.93	32.95	53.86	0.00
June	21.33	36.62	53.04	0.00
July	22.28	37.72	53.53	0.42
August	23.42	37.58	55.52	0.02
September	22.40	36.35	55.36	0.03
Sakha 2023				
May	17.28	32.86	52.17	0.00
June	21.01	36.39	52.28	0.27
July	23.38	39.78	52.54	0.00
August	23.74	38.08	55.29	0.00
September	23.51	37.78	54.21	0.00
Sids 2022				
May	17.75	34.15	41.04	0.00
June	21.77	37.40	44.36	0.00
July	22.27	37.93	43.97	0.26
August	23.50	38.45	47.76	0.33
September	21.72	36.86	50.80	0.80
Sids 2023				
May	17.97	34.08	43.64	0.07
June	22.65	37.95	41.61	0.03
July	23.57	40.24	41.68	0.00
August	23.76	39.51	46.58	0.00
September	22.66	37.64	47.00	0.00

### Experimental design and agronomic practices

The derived 15 maize hybrids and two commercial high-yielding yellow maize single-cross hybrids (SC-162 and SC-168) were sown during the summer of 2022 at two locations. The hybrids were tested under three planting densities. The applied densities were low planting density (LD: 59 524 plants ha<sup>-1</sup>), intermediate planting density (MD: 71 429 plants ha<sup>-1</sup>), and high planting density (HD: 89 286 plants ha<sup>-1</sup>) across the two locations. A split-plot design was used with three replicates in both locations. Planting densities were assigned to main plots, and maize hybrids were allocated to sub-plots. The hybrids were sown at Sakha on 20 May 2022, and at Sids on 25 May 2022. Each sub-plot consisted of four rows, 6 m long and 0.7 m wide. The hill spacing was adjusted to 16, 20, and 24 cm for HD, MD, and LD, respectively. All trials were hand-planted with two seeds per hill. The plants were thinned to one per hill 3 wk after planting. Fertilizer applications included 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, 115 kg K<sub>2</sub>O ha<sup>-1</sup>, and 300 kg N ha<sup>-1</sup>. Harvest occurred on 25 August at Sids and 15 September at Sakha.

### Recorded traits

Days to silking was recorded as the interval from planting to the emergence of silks. Plant height was measured at physiological maturity in 10 randomly selected plants. It was measured from each plot as the distance from the soil surface to the tassel. Ear height was recorded as the distance from the soil to the primary ear. Ear position was measured as the ratio of ear height to plant height. For each hybrid, 10 plants were selected, and the angle between the leaf and the vertical axis of the stem was measured at silking. Measurements were taken on the ear leaf, and the two leaves above it, and mean of these three leaves per plant was used as the leaf angle value for that plant. Leaf length (L) and maximum leaf width (W) were measured in centimeters for 10 plants per hybrid. Ear leaf area was estimated at silking using the following equation =  $L \times W \times 0.75$ .

Ten ears were randomly harvested per plot to assess the ear length and diameter, number of rows per ear, number of kernels per row, and 100-kernel weight. All ears harvested from two rows were shelled, and grain yield was recorded and expressed in  $\text{kg ha}^{-1}$ .

### Statistical analysis

Combined ANOVA for grain yield and related traits was performed using Genstat statistical software version 19.0 (VSN International, Hemel Hempstead, UK). Additive main effects and multiplicative interaction (AMMI) and Genotype plus Genotype  $\times$  Environment (GGE) models were performed using Genstat 19.0. The cluster analysis employing ggplot2, factoextra, and FactoMineR, and the heatmap used gplots in R programming. Tolerance indices were calculated using grain yield under low and high densities for both tested locations separately. Mean productivity =  $(Y_s + Y_p)/2$  (Hossain et al., 1990). Stress tolerance index =  $(Y_s \times Y_p)/(\bar{Y}_p)^2$  (Fernandez, 1992). Yield Index =  $Y_s/\bar{Y}_s$  (Gavuzzi et al., 1997); where  $Y_s$  is the grain yield under high planting density,  $Y_p$  is the grain yield under low planting density,  $\bar{Y}_p$  is the mean yield of all hybrids under low planting density, and  $\bar{Y}_s$  is the average grain yield of all hybrids under high planting density.

## RESULTS

The ANOVA for maize hybrids evaluated under three planting densities across two locations is presented in Table 3. The results revealed highly significant effects of location, planting density, and maize hybrid for most of the studied traits. The main effect of location was highly significant for all traits except the number of leaves per plant. The location main effect displayed the largest mean squares among other sources of variation. This indicates substantial environmental impact (at Sakha and Sids) on studied earliness, growth, and yield traits. Planting density also significantly affected all traits studied, confirming density effects on the agronomic performance of the assessed hybrids. The effect of maize hybrids was highly significant for all traits. This confirms the presence of substantial genetic variability among the assessed hybrids in earliness, vegetative growth, and yield-related characters. The interaction between location and planting density was highly significant for the majority of traits, suggesting different responses of maize hybrids to different densities across the two locations. The interactions between tested locations and assessed hybrids as well as between planting density and maize hybrids, were also highly significant for all traits. This indicates that the performance of the hybrids changed across the two test locations and in response to the different planting densities. Furthermore, the three-way interaction among location, planting density, and maize hybrids was significant for all traits.

The observed interactions emphasize the need for evaluating maize hybrids for yield potential and also for stability across diverse planting densities and location-specific conditions.

**Table 3.** Mean square of ANOVA analysis for earliness, growth, and yield traits of 17 maize hybrids under three planting densities across two locations. df: Degrees of freedom, statistical significance levels are indicated using \* $p < 0.05$  and \*\* $p < 0.01$ .

Source of variation	df	Days to silking	Plant height cm	Ear height cm	Ear position	Leaf angle
Location (Loc)	1	1153**	183334**	110466**	1333**	2018**
Planting density (PD)	2	18.42*	3875**	2207**	38.58**	142.1**
Genotype (Gen)	16	39.15**	1772**	617.6**	20.55**	235**
Loc × PD	2	10.66*	5949**	3081**	34.95**	48.85*
Loc × Gen	16	12.68**	674.8**	632.0**	31.23**	85.15**
PD × Gen	32	1.72**	127.1**	88.45**	7.23**	12.78**
Loc × PD × Gen	32	4.01**	171.2**	123.0**	8.79**	18.99**

Source of variation	df	Ear leaf area cm <sup>2</sup>	Number of rows per ear	Number of kernels per row	Grain yield t ha <sup>-1</sup>
Location (Loc)	1	429119**	33.60*	1885.60**	937.91*
Planting density (PD)	2	2242**	0.44	0.35	403.14**
Genotype (Gen)	16	38423**	11.03**	41.23**	188.19**
Loc × PD	2	16518**	0.92*	12.53*	5.13
Loc × Gen	16	7479**	4.66**	16.75**	16.89**
PD × Gen	32	4962**	0.72**	11.22**	18.50**
Loc × PD × Gen	32	4103**	0.94**	20.62**	3.08*

### Mean performance

The performance of days to silking and plant height for 17 single maize hybrids under three planting densities at two locations is presented in Table 4. Days to silking varied from 62.3 to 73.7 d across locations, planting densities, and hybrids. In the tested locations, the plants reached silking significantly later at the Sakha (68.1 d) compared to the Sids location (64.2 d). The higher planting densities displayed shorter days to silking compared to intermediate and low densities. Among the hybrids, Hib-6 and Hib-10 were the earliest to silk across locations, while Hib-13 was the latest. The commercial control hybrids, Hib-16 (SC-162) and Hib-17 (SC-168), exhibited mid-to-late silking. The plant height of assessed hybrids was significantly affected by location and planting density. Plant height varied from 191.7 to 303.3 cm across locations, planting densities, and hybrids. Plants were taller at the Sakha location (275.3 cm) compared to Sids (mean of 226.4 cm). The plant height exhibited a positive association with increasing planting density. Increased plant density from low to high increased plant height. At Sakha, plant height across hybrids increased from 268.9 cm at low density to 280.4 cm at high density, and also at Sids, increased from 211.5 to 238.7 cm. Considerable genetic variability for plant height was found among the hybrids. At Sakha, Hib-6 was the tallest (295.2 cm), whereas Hib-8 was the shortest (260.9 cm). Also, at Sids, Hib-16 was the tallest (250.0 cm), and Hib-1 was the shortest (mean 200.6 cm).

**Table 4.** Mean performance of days to silking and plant height for 17 single maize hybrids under three different densities at two locations. LD: Low density (59 524 plants ha<sup>-1</sup>); MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>).

Hybrid	Days to silking								Plant height (cm)							
	Sakha				Sids				Sakha				Sids			
	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean
Hib-1	68.67	68.67	67.67	68.33	66.67	62.67	65.00	64.78	255.3	262.3	270.3	262.7	191.7	195.0	215.0	200.6
Hib-2	66.00	65.00	65.33	65.44	65.33	65.00	66.33	64.44	264.0	268.7	271.7	268.1	213.3	228.3	233.3	225.0
Hib-3	69.67	68.33	67.33	68.44	65.67	65.33	64.33	65.11	267.3	268.0	277.0	270.8	205.0	213.3	240.0	219.4
Hib-4	68.67	69.67	67.33	68.56	64.33	64.33	64.00	64.22	267.7	272.3	286.3	275.4	208.3	225.0	235.0	222.8
Hib-5	68.33	68.00	67.33	67.89	64.33	63.67	64.00	64.00	272.3	273.7	275.3	273.8	225.0	225.0	243.3	231.1
Hib-6	65.00	65.00	64.00	64.67	63.00	62.67	62.67	62.78	290.3	292.0	303.3	295.2	228.3	238.3	248.3	238.3
Hib-7	70.67	69.67	69.67	70.00	68.67	63.33	63.33	65.11	280.3	286.0	290.7	285.7	191.7	221.7	243.3	218.9
Hib-8	68.00	68.67	67.67	68.11	64.67	64.67	63.67	64.33	254.7	263.0	265.0	260.9	236.7	248.3	251.7	245.6
Hib-9	69.00	69.33	66.33	68.22	66.33	63.33	63.00	64.22	258.0	276.7	278.3	271.0	196.7	226.7	226.7	216.7
Hib-10	65.33	65.00	62.67	64.33	62.67	63.33	62.67	62.89	261.0	265.3	266.0	264.1	226.7	231.7	238.3	232.2
Hib-11	68.00	66.67	66.67	67.11	63.67	63.33	63.00	63.33	284.3	284.3	292.7	287.1	206.7	236.7	238.3	227.2
Hib-12	66.00	65.67	65.00	65.56	63.00	63.00	62.33	62.78	276.3	285.3	287.3	283.0	226.7	245.0	245.0	238.9
Hib-13	73.33	73.67	73.00	73.33	67.00	65.00	65.67	65.89	251.7	273.7	277.3	267.6	193.3	223.3	226.7	214.4
Hib-14	70.67	69.67	69.33	69.89	63.00	65.00	64.00	64.00	277.0	284.3	287.0	282.8	218.3	241.7	246.7	235.6
Hib-15	70.00	71.00	68.33	69.78	65.00	63.67	63.33	64.00	266.3	285.3	272.7	274.8	200.0	226.7	230.0	218.9
Hib-16	69.67	70.67	67.67	69.33	65.00	62.67	64.00	63.89	284.3	294.3	294.0	290.9	231.7	246.7	271.7	250.0
Hib-17	68.33	68.67	67.00	68.00	66.00	65.00	64.67	65.22	260.0	268.7	271.7	266.8	195.0	218.3	225.0	212.8
Mean	68.55	68.43	67.20	68.06	64.96	63.88	63.69	64.18	268.9	276.7	280.39	275.3	211.5	228.9	238.7	226.4
LSD PD		0.41			0.34				2.28				2.23			
LSD Gen		0.97			0.85				5.42				5.31			
LSD PD × Gen		1.69			1.48				9.39				9.20			

Ear height of assessed hybrids was affected by the agro-environmental conditions of plant densities and locations (Table 5). Ear height ranged from 98.3 to 177.7 cm across locations, planting densities, and hybrids. Ear height displayed a decreased trend with planting density. Ear height was greater at Sakha across all hybrids (161.5 cm) compared to Sids (123.5 cm). Increasing planting density increased ear height from 156.7 cm at low density to 165.8 cm at high density at Sakha, and from 112.0 to 133.1 cm at Sids. Considerable genetic variation was detected among the assessed hybrids. Hib-6 possessed the highest ear height at Sakha (171.4 cm), while Hib-8 was the tallest at Sids (140.0 cm). Conversely, Hib-10 had the lowest values of ear height at Sakha (142.0 cm), and Hib-1 had the lowest at Sids (106.7 cm). Ear position ranged from 50.0% to 65.4% across locations, planting densities, and hybrids. Ear position was higher at Sakha (58.7%) than at Sids (54.5%). The effect of planting density on ear position was lower at Sakha than at Sids. At Sakha ear position increased from 58.3% at low density to 59.2% at high density and from 53.0% to 55.71% at Sids. Among the hybrids, Hib-13 and Hib-15 had the highest values of ear placement at Sakha (62.9% and 61.2%), while at Sids, Hib-8 and Hib-14 showed the highest placement (57.0% and 56.3%). Hib-10 had the lowest ear position at Sakha (53.8%), while Hib-13 at Sids (52.7 cm).

**Table 5.** Mean performance of ear height and ear position for 17 single maize hybrids under three different densities at two locations. LD: Low density (59 524 plants ha<sup>-1</sup>), MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>). LD: Low density (59 524 plants ha<sup>-1</sup>); MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>).

Hybrid	Ear height (cm)								Ear position (%)							
	Sakha			Mean	Sids			Mean	Sakha			Mean	Sids			Mean
	LD	MD	HD		LD	MD	HD		LD	MD	HD		LD	MD	HD	
Hib-1	154.7	157.3	161.3	157.8	98.33	110.0	111.7	106.7	60.58	59.97	59.68	60.08	51.30	56.43	51.95	53.23
Hib-2	152.0	159.3	163.0	158.1	113.3	125.0	128.3	122.2	57.57	59.31	60.00	58.96	53.14	54.75	55.01	54.30
Hib-3	156.3	158.3	163.0	159.2	103.3	115.0	130.0	116.1	58.51	59.09	58.85	58.81	50.49	53.91	54.17	52.86
Hib-4	160.7	162.0	177.7	166.8	106.7	121.7	132.7	120.3	60.03	59.48	62.05	60.52	51.20	54.08	56.47	53.91
Hib-5	160.7	167.7	172.0	166.8	121.7	123.3	133.3	126.1	59.00	61.27	62.48	60.92	54.11	54.81	54.80	54.58
Hib-6	167.3	169.3	177.7	171.4	125.0	131.7	141.7	132.8	57.63	57.99	58.57	58.07	54.75	55.26	57.05	55.69
Hib-7	163.0	168.7	169.0	166.9	108.3	116.7	141.7	122.2	58.15	58.98	58.14	58.42	56.55	52.63	58.23	55.80
Hib-8	136.0	156.3	156.7	149.7	133.3	141.7	145.0	140.0	53.40	59.45	59.12	57.32	56.34	57.05	57.62	57.00
Hib-9	150.3	166.7	168.0	161.7	103.3	119.3	121.7	114.8	58.28	60.24	60.36	59.63	52.59	52.65	53.69	52.98
Hib-10	138.7	144.0	143.3	142.0	113.3	126.7	131.7	123.9	53.13	54.27	53.88	53.76	50.02	54.69	55.25	53.32
Hib-11	164.3	164.3	173.0	167.2	106.7	125.0	131.7	121.1	57.80	57.80	59.11	58.23	51.65	52.82	55.26	53.24
Hib-12	151.3	156.7	158.0	155.3	118.3	136.7	140.0	131.7	54.77	54.91	54.99	54.89	52.22	55.78	57.14	55.05
Hib-13	164.7	165.7	173.7	168.0	101.0	115.0	123.3	113.1	65.43	60.54	62.62	62.86	52.28	51.49	54.43	52.73
Hib-14	165.0	169.3	171.0	168.4	115.0	138.3	145.0	132.8	59.57	59.56	59.58	59.57	52.99	57.24	58.78	56.34
Hib-15	164.7	167.7	172.0	168.1	103.3	125.0	128.3	118.9	61.83	58.76	63.08	61.22	51.67	55.15	55.80	54.20
Hib-16	160.7	162.7	162.3	161.9	125.0	138.3	151.7	138.3	56.62	55.41	55.22	55.75	54.00	56.16	55.84	55.33
Hib-17	152.7	157.7	157.7	156.0	108.3	121.7	125.0	118.3	59.01	59.02	58.04	58.69	55.54	55.77	55.52	55.61
Mean	156.6	162.0	165.8	161.5	112.02	125.4	133.1	123.5	58.31	58.59	59.16	58.69	52.99	54.75	55.71	54.48
LSD <sub>PD</sub>		0.92				1.17				0.38				0.64		
LSD <sub>Gen</sub>		2.18				2.78				0.91				1.52		
LSD <sub>PDxGen</sub>		3.77				4.81				1.58				2.63		

Leaf angle ranged from 19.7° to 43.0° across locations, planting densities, and hybrids (Table 6). At Sakha, the leaf angle decreased from 35.3° at low density to 32.1° at high density. At Sids decreased from 28.6° at low density to 27.2° at low density. Considerable genetic diversity for leaf angle was detected. At Sakha, Hib-5 and Hib-14 displayed the widest leaf angles (41.22° and 41.11°, respectively), whereas Hib-8 exhibited the most erect leaf angle (21.67°). At Sids, Hib-11 exhibited the widest angle (33.76°) and Hib-1 the narrowest one (23.87°). Ear leaf area ranged between 488.3 to 834 cm<sup>2</sup> across locations, planting densities, and hybrids. Significant effect of the tested locations was observed on ear leaf area (Table 6). Sakha exhibited significantly larger ear leaves (676.6 cm<sup>2</sup>) compared to Sids (601.7 cm<sup>2</sup>). Also, different responses of assessed hybrids to planting density were detected. Increasing plant density decreased ear leaf area at both locations. Ear leaf area decreased from 696.5 cm<sup>2</sup> at low density to 655.6 cm<sup>2</sup> high density at Sakha, and from 634.2 to 563.5 cm<sup>2</sup>. The hybrids Hib-16 and Hib-17 were exhibited superior ear leaf area at Sakha (817.1 and 776.9 cm<sup>2</sup>) and Sids (661.3 and 656.4 cm<sup>2</sup>). Also, the hybrids, Hib-2, Hib-3, Hib-6, and Hib-11 displayed larger ear leaf areas.

**Table 6.** Mean performance of leaf angle and ear leaf area for 17 single maize hybrids under three different planting densities at two locations. LD: Low density (59 524 plants ha<sup>-1</sup>); MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>).

Hybrid	Leaf angle (%)								Ear leaf area (cm <sup>2</sup> )							
	Sakha				Sids				Sakha				Sids			
	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean
Hib-1	25.67	26.33	25.33	25.78	22.27	26.33	23.00	23.87	620.3	589.1	582.0	597.1	574.7	570.7	499.0	548.1
Hib-2	36.00	27.00	30.00	31.00	24.13	25.07	23.07	24.09	748.3	693.0	660.3	700.5	687.3	687.0	579.9	651.4
Hib-3	37.33	37.00	30.33	34.89	30.40	27.73	28.40	28.84	682.5	699.0	762.6	714.7	644.5	591.6	551.8	595.9
Hib-4	33.33	33.33	35.33	34.00	28.53	28.87	24.87	27.42	699.1	660.3	591.6	650.3	617.0	581.5	548.8	582.4
Hib-5	43.00	38.00	42.67	41.22	28.20	33.07	32.27	31.18	574.2	635.6	608.7	606.1	645.3	560.8	547.3	584.4
Hib-6	35.00	27.00	30.00	30.67	30.73	30.27	25.30	28.77	780.4	729.9	682.6	730.9	645.6	627.9	582.4	618.7
Hib-7	28.00	24.67	25.67	26.11	25.27	25.13	24.80	25.07	746.7	725.3	692.3	721.4	696.8	618.8	488.3	601.3
Hib-8	25.00	19.67	20.33	21.67	27.40	29.13	26.60	27.71	673.7	638.4	625.8	646.0	606.8	597.5	564.4	589.5
Hib-9	40.00	32.33	33.67	35.33	26.53	27.53	21.27	25.11	592.9	602.0	640.9	611.9	578.9	574.1	571.9	575.0
Hib-10	33.00	30.33	32.67	32.00	31.70	28.73	29.20	29.88	664.0	636.8	619.1	640.0	643.2	617.3	559.0	606.5
Hib-11	35.67	36.67	30.67	34.33	34.70	34.03	32.53	33.76	727.8	732.0	694.0	717.9	647.5	615.8	580.0	614.4
Hib-12	42.33	36.67	32.00	37.00	31.67	33.73	30.53	31.98	695.5	670.5	658.8	674.9	624.7	602.2	592.4	606.4
Hib-13	36.33	31.33	33.67	33.78	23.13	29.47	24.73	25.78	689.3	675.6	645.2	670.0	591.4	584.0	552.2	575.8
Hib-14	41.00	41.00	41.33	41.11	32.53	31.07	34.13	32.58	662.9	630.4	584.3	625.9	597.7	565.3	633.4	598.8
Hib-15	34.67	34.33	35.00	34.67	27.87	23.73	25.67	25.76	637.0	603.9	559.0	599.9	592.6	589.8	503.8	562.1
Hib-16	37.33	36.33	32.67	35.44	32.70	26.13	29.53	29.46	834.0	825.0	792.4	817.1	704.9	675.4	603.6	661.3
Hib-17	36.00	40.33	33.67	36.67	29.20	26.07	26.07	27.11	812.6	772.8	745.2	776.9	683.3	663.8	622.0	656.4
Mean	35.27	32.49	32.06	33.27	28.64	28.59	27.17	28.14	696.5	677.6	655.6	676.6	634.2	607.3	563.5	601.7
LSD PD		0.65				0.78				6.13				4.39		
LSD Gen		1.55				1.85				12.22				10.45		
LSD		2.68				3.20				21.17				18.10		
PDxGen																

Number of rows per ear varied from 12.93 to 17.73 across location, planting density, and hybrids (Table 7). Sakha produced a higher number of rows per ear (15.1 rows) than Sids (14.4 rows). Furthermore, the number of rows per ear decreased when the planting density increased across both sites. Number of rows per ear decreased from 15.4 rows at low density to 14.8 rows at high density at Sakha, and from 14.9 to 13.9 rows at Sids. Genotypic variation was considerable across locations; Hib-1 and Hib-8 had the highest number of rows per ear at both Sakha (17.5 and 17.6) while Hib-1 and Hib-9 at Sids (16.9 and 15.0). Number of kernels per row varied from 32.3 to 48.6 across location, planting density, and hybrids (Table 7). Sakha had higher number of kernels per row (43.2) compared to Sids (38.2). The assessed hybrids displayed different responses to planting density. The number of kernels per row decreased when plant density increased at both locations. Number of kernels per row decreased from 44.9 rows at low density to 41.6 rows at high density at Sakha, and from 40.1 to 36.0 rows at Sids. Hib-16 and Hib-17 exhibited the highest number of kernels per row at Sakha (46.8 and 45.6), while at Sids Hib-2 and Hib-3 (40.8 and 42.1). Grain yield varied from 6.3 to 13.6 t ha<sup>-1</sup> across location, planting density, and genotype (Table 8). Sakha exhibited higher grain yield (10.2 t ha<sup>-1</sup>) than Sids (9.0 t ha<sup>-1</sup>). Grain yield increased at high density than at low density at both locations. At Sakha, grain yield increased from 9.7 t ha<sup>-1</sup> at low density to 10.9 t ha<sup>-1</sup> at high density, and from 8.4 to 9.7 t ha<sup>-1</sup> at Sids. Hib-6 and Hib-16 exhibited the highest grain yield at both Sakha (12.7 and 12.3 t ha<sup>-1</sup>) and Sids (10.5 and 9.8 t ha<sup>-1</sup>). Also, Hib-4, Hib-11, Hib-16 and Hib-17 displayed high and stable yields across locations.

**Table 7.** Mean performance of number of rows per ear and number of kernels per row for 17 single maize hybrids under three different planting densities at two locations. LD: Low density (59 524 plants ha<sup>-1</sup>); MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>).

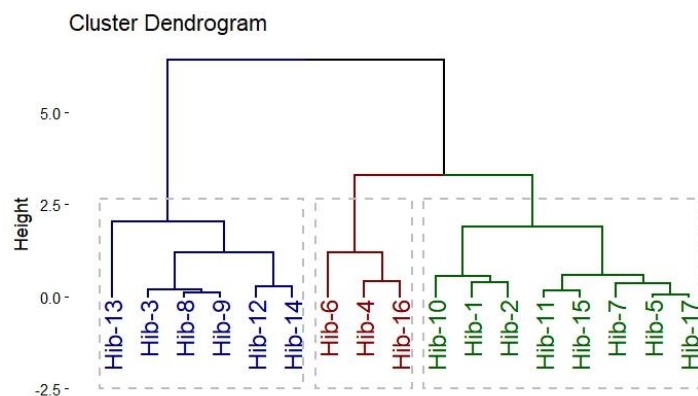
Hybrid	Number of rows per ear								Number of kernels per row							
	Sakha				Sids				Sakha				Sids			
	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean	LD	MD	HD	Mean
Hib-1	17.60	17.47	17.37	17.48	17.07	16.67	17.07	16.93	47.47	44.20	42.27	44.64	39.93	38.67	32.27	36.96
Hib-2	15.33	14.93	14.13	14.8	15.13	14.53	13.73	14.47	44.67	41.93	41.53	42.71	43.40	41.47	37.47	40.78
Hib-3	14.93	14.67	14.40	14.67	15.53	14.80	13.87	14.73	44.73	43.43	41.87	43.34	43.33	41.67	41.27	42.09
Hib-4	15.50	14.67	14.67	14.94	16.27	14.27	14.13	14.89	45.33	44.67	43.07	44.36	43.80	39.67	39.40	40.96
Hib-5	14.53	14.67	14.53	14.58	14.27	14.13	13.87	14.09	44.67	43.93	43.03	43.88	40.30	38.80	34.00	37.70
Hib-6	15.63	15.60	15.33	15.52	14.60	14.40	13.73	14.24	44.80	43.40	43.20	43.80	38.43	37.47	33.83	36.58
Hib-7	16.67	16.00	15.33	16.00	13.73	13.33	13.07	13.38	46.50	43.40	41.27	43.72	40.13	38.63	36.23	38.33
Hib-8	17.73	17.60	17.47	17.60	14.27	14.13	13.60	14.00	45.53	44.13	42.07	43.91	40.33	37.73	37.13	38.40
Hib-9	15.20	14.80	14.70	14.90	15.07	14.93	14.87	14.96	44.00	40.07	38.87	40.98	42.13	37.00	34.13	37.76
Hib-10	15.87	15.47	15.37	15.57	14.80	14.53	14.40	14.58	43.33	41.93	36.53	40.60	40.23	35.40	34.27	36.63
Hib-11	14.67	14.27	14.13	14.36	14.53	14.00	13.07	13.87	45.60	43.20	42.47	43.76	39.30	38.47	33.97	37.24
Hib-12	14.07	13.73	13.33	13.71	14.13	14.00	13.07	13.73	42.87	40.60	41.87	41.78	36.93	39.13	39.60	38.56
Hib-13	14.40	14.30	13.87	14.19	15.20	14.13	12.93	14.09	42.13	40.87	40.60	41.20	36.67	35.80	34.53	35.67
Hib-14	14.40	14.27	13.87	14.18	14.67	14.13	13.07	13.96	43.67	41.67	41.27	42.20	37.73	36.07	34.50	36.10
Hib-15	14.33	14.40	14.23	14.32	15.20	13.87	13.80	14.29	43.20	39.53	39.00	40.58	38.33	39.60	32.80	36.91
Hib-16	15.07	14.00	13.73	14.27	14.33	13.73	13.60	13.89	48.63	46.43	45.37	46.81	40.40	40.23	38.47	39.70
Hib-17	15.20	14.73	14.53	14.82	15.07	14.80	14.67	14.84	46.73	46.60	43.47	45.60	39.40	39.20	38.73	39.11
Mean	15.36	15.03	14.76	15.05	14.93	14.38	13.91	14.41	44.93	42.94	41.63	43.17	40.05	38.53	36.04	38.20
LSD PD		0.23				0.18				0.39				0.46		
LSD Gen		0.55				0.42				0.93				1.09		
LSD PD×Gen		0.95				0.74				1.62				1.89		

**Table 8.** Mean performance of grain yield for single maize hybrids under three different planting densities at two locations. LD: Low density (59 524 plants ha<sup>-1</sup>); MD: intermediate density (71 429 plants ha<sup>-1</sup>); HD: high density (89 286 plants ha<sup>-1</sup>).

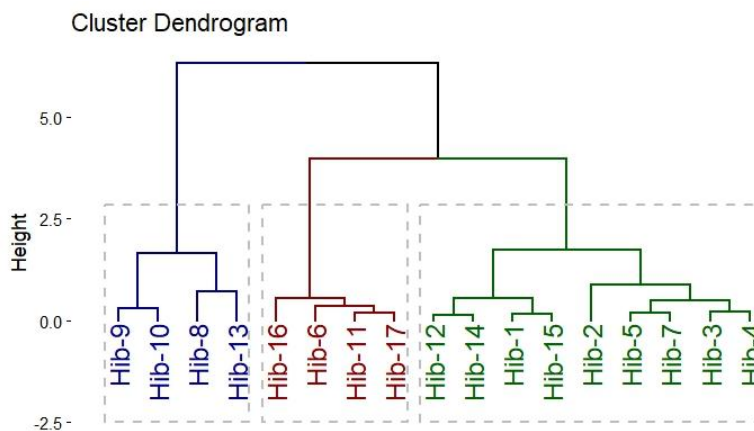
Hybrid	Grain yield (t ha <sup>-1</sup> )							
	Sakha				Sids			
	LD	MD	HD	Mean	LD	MD	HD	Mean
Hib-1	9.68	9.21	10.61	9.84	8.25	8.33	9.48	8.69
Hib-2	9.30	11.24	11.45	10.66	8.05	9.36	10.04	9.15
Hib-3	9.28	10.38	9.50	9.72	7.61	9.32	9.25	8.73
Hib-4	11.13	10.35	11.50	10.99	9.16	9.09	10.28	9.51
Hib-5	10.26	9.87	10.94	10.36	8.87	9.18	9.78	9.27
Hib-6	12.13	12.23	13.60	12.66	9.92	10.22	11.24	10.46
Hib-7	10.11	9.67	12.24	10.67	8.62	9.04	10.46	9.37
Hib-8	9.00	6.33	8.80	8.04	7.55	6.71	8.33	7.53
Hib-9	9.15	8.23	9.37	8.92	7.54	7.51	8.87	7.97
Hib-10	9.43	8.59	10.99	9.67	8.53	7.75	9.84	8.71
Hib-11	10.72	11.75	12.49	11.65	8.96	10.07	10.65	9.90
Hib-12	7.93	9.25	10.33	9.17	7.49	8.76	9.42	8.56
Hib-13	6.65	6.90	9.51	7.69	7.38	7.37	9.05	7.94
Hib-14	8.29	9.43	9.18	8.97	7.49	8.84	8.77	8.37
Hib-15	10.56	9.18	10.09	9.94	8.87	8.49	9.37	8.91
Hib-16	11.26	12.74	12.94	12.31	9.47	9.91	10.12	9.83
Hib-17	10.21	11.94	11.54	11.23	8.83	9.92	10.51	9.75
Mean	9.71	9.84	10.89	10.15	8.39	8.82	9.73	8.98
LSD PD		0.64				0.73		
LSD Gen		1.53				1.74		
LSD PD × Gen		2.65				3.01		

### Hybrid classification based on yield traits

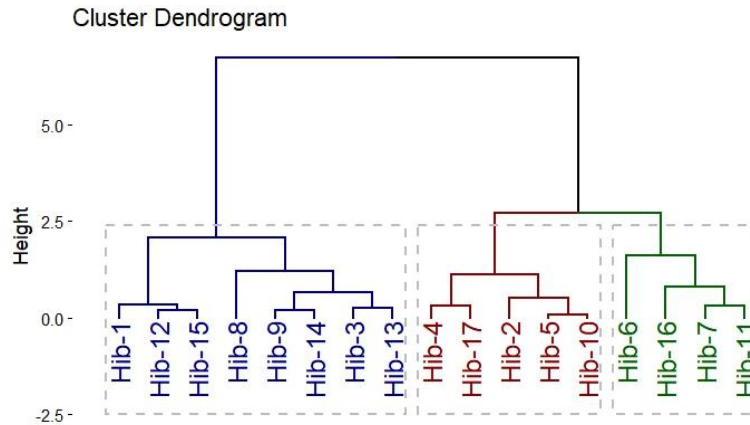
Hierarchical cluster analysis was applied to classify the 17 maize hybrids based on their yield-related traits under three planting density conditions (Figures 1-3). The dendrogram revealed three distinct clusters under low-density conditions (Figure 1). The red group included Hib-6, Hib-4, and Hib-16, displayed higher yield traits and superior performance under low planting density. The green group comprised Hib-10, Hib-1, Hib-2, Hib-11, Hib-15, Hib-7, Hib-5, and Hib-17 displayed intermediate performance. The blue contained Hib-13, Hib-8, Hib-9, Hib-12, and Hib-14, which exhibited the lowest performance under low planting density. Similarly, under intermediate planting density, the hierarchical cluster classified the maize hybrids into three groups (Figure 2). The red group included Hib-16, Hib-6, Hib-11, and Hib-17. These hybrids possessed higher yield traits and superior performance under intermediate planting density. The green group comprised Hib-12, and Hib-14, Hib-1, Hib-15, Hib-2, Hib-5, Hib-7, Hib-3, and Hib-4 exhibited intermediate yield performance. While the blue group contained Hib-9, Hib-10, Hib-8, and Hib-13 displayed the lowest yield performance under intermediate planting density. Furthermore, under high planting density, the hierarchical cluster classified the hybrids into three groups (Figure 3). The red group included Hib-4, Hib-17, Hib-2, Hib-5, and Hib-10 displayed higher yield traits and superior performance under high planting density. The green group, comprised Hib-6, Hib-16, Hib-7, and Hib-11. These hybrids exhibited intermediate yield performance. While the blue group contained Hib-1, Hib-12, Hib-15, Hib-8, Hib-9, Hib-14, Hib-3, and Hib-13. These hybrids displayed the lowest yield performance under high planting density.



**Figure 1.** Hierarchical cluster dendrogram of 17 maize hybrids based on yield traits under low planting density conditions.

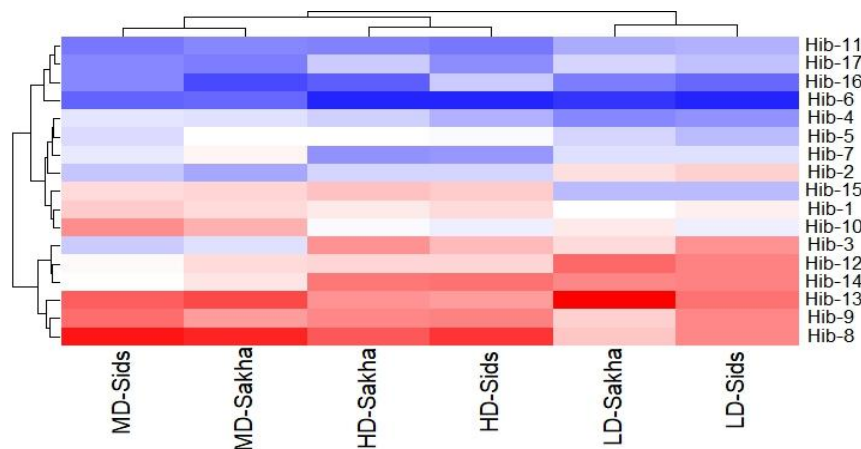


**Figure 2.** Hierarchical cluster dendrogram of 17 maize hybrids based on yield traits under intermediate planting density.



**Figure 3.** Hierarchical cluster dendrogram of 17 maize hybrids based on yield traits under high planting density.

Additionally, the hierarchical clustered heatmap classified the hybrids based on their grain yield across the tested six agro-environments (Figure 4). The hybrids are distinctly classified into three groups, with blue color for high performance and red for low performance. The first group included high-performing genotype hybrids Hib-11, Hib-17, Hib-16, and Hib-6. These hybrids exhibit blue cells across most environments, confirming their superior and stable yield potential. Hence, these hybrids could be classified as high performers. The hybrids, Hib-4, Hib-5, Hib-7, Hib-2, Hib-15, Hib-1, and Hib-10 exhibited intermediate performers with a variety of blue and red colors. The hybrids Hib-3, Hib-12, Hib-14, Hib-13, Hib-9, and Hib-8 displayed consistent red cells are through multiple agro-environments. Therefore, these could be considered as low performers. This indicates their poor adaptability and low productivity under the tested conditions. In addition, the hierarchical clustered heatmap classified the six testing environments based on the grain yield performance of the assessed maize hybrids. The dendrogram grouped the environments into two distinct clusters based on planting density. The first cluster comprised the low density at Sakha and Sids locations. The second cluster contained intermediate and high density at both locations.



**Figure 4.** Hierarchical clustered heatmap of grain yield for the assessed 17 maize hybrids under three planting densities across two locations. Blue color implies high values and red color reveal low values for the studied traits. MD-Sids: Intermediate planting density at Sids; MD-Sakha: intermediate planting density at Sakha; HD-Sakha: high planting density at Sakha; HD-Sids: high planting density at Sids; LD-Sakha: low planting density at Sakha; LD-Sids: low planting density at Sids.

### Density tolerance indices

The stress tolerance indices for all hybrids across the two locations are presented in Table 9. These indices estimate the hybrid performance under low and high planting densities. At Sakha, mean productivity varied across hybrids ranging from 8.08 (Hib-13) to 12.87 (Hib-6). Hib-6 exhibited the highest mean productivity followed by Hib-16 (12.10), and Hib-11 (11.61). While Hib-13 and Hib-14 displayed the lowest values (8.08 and 8.74, respectively) followed by Hib-8 (8.9), Hib-12 (9.13) and Hib-9 (9.26). Moreover, the stress tolerance index displayed substantial variation in density tolerance capacity. Hib-6 demonstrated the highest stress tolerance index (1.75), followed by Hib-16 (1.55), and Hib-11 (1.42). Conversely, Hib-13 (0.67), Hib-14 (0.81), Hib-12 (0.87), and Hib-9 (0.91) showed lower stress tolerance index. This reflects greater sensitivity to high-density conditions. Hib-6 maintained the highest yield index (1.25), followed by Hib-11 (1.15), Hib-7 (1.12), and Hib-16 (1.19). In contrast, Hib-3, Hib-9, Hib-13, and Hib-14 exhibited a yield index below 0.87. Likewise, at Sids, mean productivity ranged from 7.94 (Hib-8) to 10.58 (Hib-6). Hib-6 maintained the highest mean productivity (10.58). Hib-11 (9.81) and Hib-16 (9.80) also exhibited high mean productivity at Sids. Besides, Hib-6 displayed the highest stress tolerance index (1.18), followed by Hib-16 (1.02) and Hib-11 (1.01). Hib-8, Hib-9, Hib-13, and Hib-14 exhibited very low stress tolerance indices at Sids (0.67-0.71). Hib-6 displayed the highest yield index (1.03), followed by Hib-11 (0.98), Hib-17 (0.97), and Hib-7 (0.96). Whereas Hib-8, Hib-14, Hib-9, Hib-13, and Hib-3 recorded the lowest yield index.

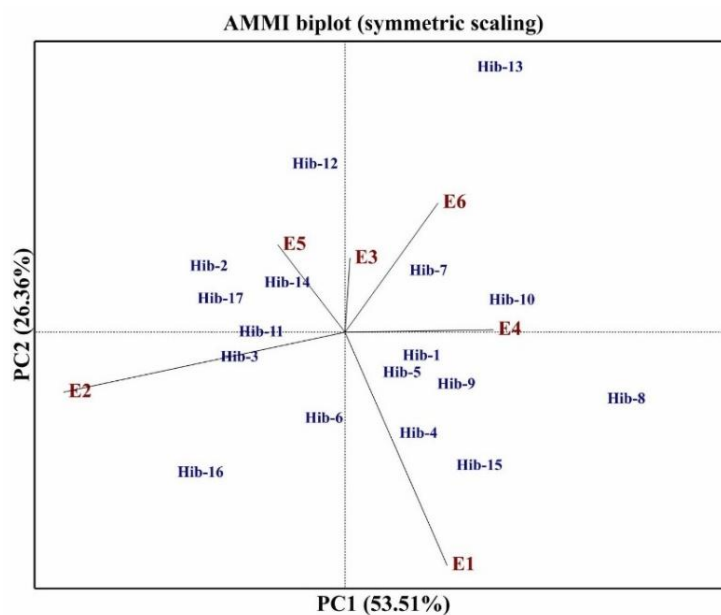
**Table 9.** Tolerance indices for 17 single maize hybrids evaluated under low and high planting densities at two locations (Sakha and Sids).

Hybrid	Sakha			Sids		
	Mean productivity	Stress tolerance index	Yield index	Mean productivity	Stress tolerance index	Yield index
Hib-1	10.15	1.09	0.97	8.87	0.83	0.87
Hib-2	10.38	1.13	1.05	9.05	0.86	0.92
Hib-3	9.39	0.93	0.87	8.43	0.75	0.85
Hib-4	11.32	1.36	1.06	9.72	1.00	0.94
Hib-5	10.60	1.19	1.00	9.33	0.92	0.90
Hib-6	12.87	1.75	1.25	10.58	1.18	1.03
Hib-7	11.18	1.31	1.12	9.54	0.96	0.96
Hib-8	8.90	0.84	0.81	7.94	0.67	0.77
Hib-9	9.26	0.91	0.86	8.21	0.71	0.81
Hib-10	10.21	1.10	1.01	9.19	0.89	0.90
Hib-11	11.61	1.42	1.15	9.81	1.01	0.98
Hib-12	9.13	0.87	0.95	8.46	0.75	0.87
Hib-13	8.08	0.67	0.87	8.22	0.71	0.83
Hib-14	8.74	0.81	0.84	8.13	0.70	0.81
Hib-15	10.33	1.13	0.93	9.12	0.88	0.86
Hib-16	12.10	1.55	1.19	9.80	1.02	0.93
Hib-17	10.88	1.25	1.06	9.67	0.98	0.97

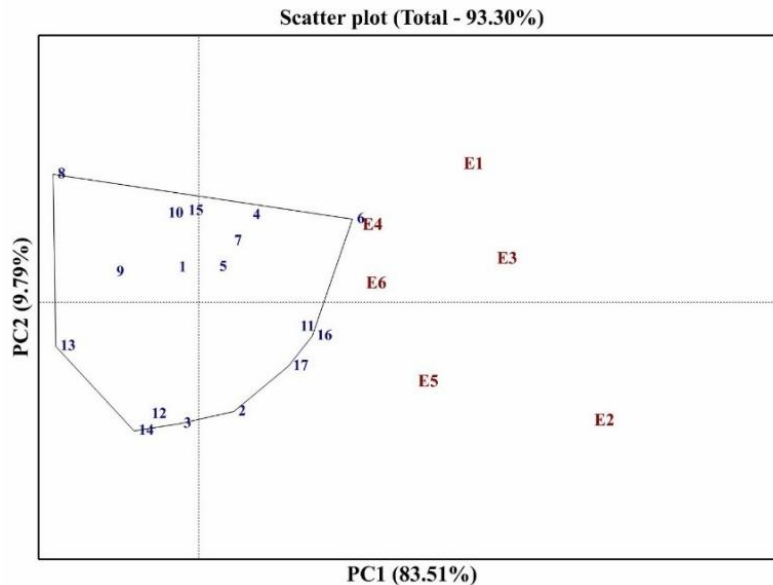
### Yield stability

The first two principal components (PC) of AMMI explained 53.51% and 26.36% of the interaction sum of squares, respectively (Figure 5). PC1 and PC2 together accounted for 79.87% of the G×E sum of squares. This proportion confirmed that the biplot could accurately present the responses of assessed hybrids across the six agro-environments. The hybrids, Hib-1, Hib-5, and Hib-11, located close to the origin and exhibited small scores of PC1 and PC2. These hybrids displayed the lowest interaction with environments. Therefore, these hybrids showed high phenotypic stability and relatively consistent performance across environments. Although their

mean yields were moderate rather than the other hybrids. This suggests their suitability where yield stability is prioritized over productivity. In contrast, Hib-13, Hib-12, Hib-16, Hib-15, and Hib-8, positioned far from the origin and had large interaction scores. This indicates strong sensitivity to environmental changes. High-yielding hybrids Hib-6, Hib-11, Hib-17, Hib-16, Hib-4, and Hib-7 across environments showed relatively moderate PC scores. This indicates desirable adaptation to several environments. The vectors of test environments differed in length indicating differences in their discriminating ability. Furthermore, the GGE biplot differentiated among the assessed hybrids and test environments (Figure 6). The first two PCs together explained 93.30% of the total variation (PC1 = 83.51%, PC2 = 9.79%). Most of the assessed hybrids were grouped within a polygon on the negative side of PC1. Whereas few hybrids located outside or close to the polygon margins. Hybrids Hib-1, Hib-5, Hib-7, Hib-9, and Hib-11 clustered near the biplot origin. These hybrids exhibited high stability across environments with moderate yield performance. In contrast, Hib-8, Hib-6, Hib-13, Hib-14, Hib-2, Hib-3, Hib-17, and Hib-16 were positioned far from the origin. Hybrids located at the outer vertices of the polygon. The six tested environments were separated along PC1. This confirms strong environmental contrasts mainly driven by planting density and location. Environments E1 (low density at Sakha), E2 (intermediate density at Sakha), E3 (high density at Sakha) were located away from the origin. This indicates high discriminating ability and strong contribution to the Genotype  $\times$  Environment interaction for grain yield. By contrast, E4 (low density at Sids), E5 (intermediate density at Sids) and E6 (high density at Sids), were positioned closer to the origin.



**Figure 5.** Additive main effects and multiplicative interaction (AMMI) biplot of grain yield for 17 maize hybrids across six agro-environments. E1: Low planting density at Sakha; E2: intermediate planting density at Sakha; E3: high planting density at Sakha; E4: low planting density at Sids; E5: intermediate planting density at Sids; E6: high planting density at Sids.



**Figure 6.** Genotype plus Genotype by Environment (GGE) biplot presenting genotype by environment interaction for grain yield of 17 maize hybrids (1-17) across six agro-environments (E1-E6). E1: Low planting density at Sakha; E2: intermediate planting density at Sakha; E3: high planting density at Sakha; E4: low planting density at Sids; E5: intermediate planting density at Sids; E6: high planting density at Sids.

## DISCUSSION

Planting density and maize hybrids are important factors of maize productivity under different locations (Zhang et al., 2025). Therefore, understanding the interaction of these factors is essential for designing proper cropping systems. This supports sustaining high grain yield and maintaining stability across contrasting locations and seasons. In the present study, newly developed single-crosses were derived using diverse yellow maize inbred lines. The parental inbred lines were chosen after preliminary screening trials that evaluated their adaptation under high planting density conditions. Consequently, it is important to assess the agronomic performance and adaptation of derived hybrids across contrasting planting densities and locations. The results demonstrated that grain yield and its related traits were significantly affected by the tested locations, planting density, the evaluated hybrids, and their interactions. The highly significant mean squares of locations and plant densities confirmed that the environmental variations and the imposed density gradients created contrasting growing conditions. The significant two- and three-way interactions indicated that no single factor acted in isolation. The hybrid performance was the outcome of complex genotype by environment by management relationships. This emphasizes the necessity of multi-environment testing to identify broadly adapted and density-tolerant material as suggested by Kachapur et al. (2023) and Shiri et al. (2025).

Plant growth and phenology responded consistently to the environmental and management gradients. Plants grown at Sakha exhibited taller plants, higher ear placement, larger ear leaf area, more rows per ear, more kernels per row, and higher grain yield than at Sids. This reflects more favorable soil fertility and organic matter status at Sakha. Plant height and ear height displayed higher planting density at both sites. This suggests that the hybrids responded to intra-specific competition by allocating more resources to vertical growth to avoid shade. In contrast, traits related to reproductive sink capacity, such as number of rows per ear and kernels per row, decreased with increasing density. This indicates that stress during flowering and grain set at high density restricted ear development. Nevertheless, grain yield per hectare increased from low to high density at both locations. Du et al. (2021) and Tian et al. (2022) elucidated that slightly high densities increased maize yield even when individual plant productivity declined. This confirms that higher number of plants per unit area compensated for the per-plant reduction in ear traits.

Substantial genetic variability among the 17 hybrids was detected for all measured traits. This provides opportunities for improving yield potential and density tolerance. Certain hybrids, such as Hib-6, Hib-11, Hib-16, Hib-17, Hib-7, Hib-4, and Hib-5, combined tall stature, favorable ear position, large ear leaf area, more kernels per row, and superior grain yield across locations and densities. These hybrids possess complementary alleles for yield-determining traits and morphological attributes. Hence, they could be considered promising candidates for commercial cultivation. Moreover, these hybrids could be exploited in maize breeding programs aimed at intensifying maize production. In contrast, hybrids Hib-8, Hib-9, Hib-12, Hib-13, and Hib-14 showed lower morphological attributes and yield traits. This indicates that they are less suitable for the tested environments and planting densities. Nevertheless, these hybrids could still be useful as sources of specific traits and are less promising as cultivars under intensive systems. Similar findings of significant genetic variability and density-tolerant hybrids have been reported in previous studies. He et al. (2022) and Wang et al. (2025) evaluated maize hybrids under different planting densities. They detected significant genetic variability and identified promising hybrids across densities. This confirms the potential of breeding to enhance intensive maize production.

Multivariate analyses are essential to clarify the structure of genotype performance and adaptation (Wang et al., 2023). These statistical tools provide useful information from different traits and environments into informative components (Meena et al., 2025). They can separate broadly adapted and poorly adapted genotypes more effectively than univariate comparisons (Stella et al., 2025). The hierarchical clustering under each planting density grouped the hybrids into distinct clusters. Under low density, the hybrids Hib-6, Hib-4, and Hib-16 displayed superior performance. This suggests that they exploit abundant resources efficiently. Hence, these hybrids could be well-suited to less intensive systems with wider spacing. Under intermediate density, Hib-16, Hib-6, Hib-11, and Hib-17 displayed superior performance. This indicates that these hybrids possess robust architecture and assimilate-partitioning patterns that enable to maintain performance under competition. Under high density, the best group shifted to include Hib-4, Hib-17, Hib-2, Hib-5, and Hib-10, whereas Hib-6 and Hib-16 moved to an intermediate cluster. This shows that certain hybrids express their maximum advantage under strong competition, while others perform best at moderate ones. This density-specific clustering demonstrated that breeding for high-density tolerance should consider the target level. Consequently, selection at one density may not ensure superiority under other densities. The heatmap of grain yield across the agro-environments provided an integrated view of hybrid adaptation and environmental relationships. Hib-11, Hib-17, Hib-16, and Hib-6 maintained high performance across most environments. This suggests that they combine yield potential with relative stability. A second group of Hib-4, Hib-5, Hib-7, Hib-2, Hib-15, Hib-1, and Hib-10 showed intermediate performance and more variable responses. The yield performance of these hybrids is strongly influenced by the interaction of planting density and location. These hybrids may be valuable for specific environments where their performance can be exploited. The third group, Hib-3, Hib-12, Hib-14, Hib-13, Hib-9, and Hib-8 displayed lowest performance. These hybrids displayed poor adaptation across environments and are unlikely to contribute directly to productivity improvement under the tested conditions. On the environmental level, the low-density treatments of both locations were clustered in one group. While intermediate and high densities of both locations were clustered in another group. This indicates that planting density displayed a stronger effect on hybrid performance than the difference between the tested locations (Sakha and Sids). This pattern reinforces that plant population is a major factor of Genotype  $\times$  Environment interaction in intensive maize systems. Similar clustering patterns and hybrid groupings have been documented in previous studies under varying plant populations. Díaz-González et al. (2025) and Nagendrachi et al. (2025) applied hierarchical analyses to differentiate the assessed hybrids based on their performance across different densities. These findings confirm that multivariate clustering effectively differentiates promising high-density tolerant hybrids for intensive systems.

The additive main effects and multiplicative interaction (AMMI) analysis showed that the hybrids Hib-1, Hib-5, and Hib-11 are located near the origin. These hybrids exhibited small interaction scores and more stable performance across environments. Therefore, these hybrids are suitable for yield reliability. In contrast, the hybrids Hib-13, Hib-12, Hib-16, Hib-15, and Hib-8 placed far from the origin. These hybrids are associated with specific high-density or high-yield environments. Therefore, these hybrids showed strong sensitivity to environmental changes. The Genotype plus Genotype by Environment (GGE) biplot provided additional insight into the pattern of hybrid adaptation. Most hybrids were grouped within a polygon on the negative side of PC1.

While the hybrids Hib-8, Hib-6, Hib-13, Hib-14, Hib-2, Hib-3, Hib-17, and Hib-16 are located near the polygon vertices and far from the origin. In contrast, hybrids such as Hib-1, Hib-5, Hib-7, Hib-9, and Hib-11 are located close to the origin. This reflects minimal interaction and high stability. The clear separation of environments along PC1, with E1, E2, and E3 at Sakha located away from the origin; while Sids environments E4, E5, and E6 are positioned closer to the origin. This confirms that planting density and location jointly created strong environmental contrasts. Sakha conditions were more informative for distinguishing hybrid performance, while Sids environments behaved as average sites with lower discriminatory power. Similarly, Jahan et al. (2024) and Shiri et al. (2025) applied AMMI and GGE biplot to identify stable hybrids in multi-environment trials. The results validated the usefulness of AMMI and GGE for precise identification of stable hybrids under density-stressed systems.

Density tolerance indices provided further insight into hybrid responses to density stress under arid conditions. Hib-6, Hib-11, and Hib-16 exhibited superior performance at both Sakha and Sids. This indicates that these hybrids combine high yield potential with tolerance mechanisms. This enables these hybrids to sustain productivity under high plant populations. In particular, the tolerance indices of Hib-6 presented strong performance across locations. This hybrid possesses the capacity to maintain assimilation partitioning under intensified competition. By contrast, Hib-8, Hib-9, Hib-13, and Hib-14 recorded the lowest tolerance indices at both locations. This indicates their sensitivity to high planting density. Moreover, the results demonstrated that high grain yield at low density does not necessarily translate into resilience under high plant density. These findings support that selection for density tolerance should be applied under contrasting planting densities and environments. Similarly, Dhaliwal et al. (2021) and Ndou et al. (2021) applied tolerance indices to identify tolerant hybrids under high-density conditions. These results reinforce the reliability of tolerance indices for breeding decisions in intensive high-density maize production. Overall, breeding for intensive maize production should prioritize high yield potential with tolerance to high planting densities.

## CONCLUSIONS

This study demonstrated that grain yield and its related traits in yellow maize are strongly affected by the effects of environment, planting density, hybrids, and their interactions. The contrasting conditions between the tested locations and the imposed density gradient generated substantial variation in plant architecture, ear traits, and yield. This confirmed that plant population is a major factor of productivity and genotype by environment interaction in intensive maize systems. The newly developed single-cross hybrids displayed wide genetic variability. The hybrids Hib-6, Hib-11, Hib-7, Hib-16, and Hib-17 were identified as promising hybrids. These hybrids combined high grain yield with desirable morphological traits and good performance across most environments. Moreover, density tolerance indices confirmed their stable and productive performance under high planting densities across both locations. These genotypes demonstrated superior stress tolerance and yield maintenance. They could be considered candidates for intensive maize production systems in arid environments. Moreover, they could be utilized as a source for future improvement in maize programs aimed at intensifying maize production. Their consistent performance supports targeted breeding efforts to develop density-adapted hybrids. Multivariate analyses, including cluster analysis, heatmap classification, additive main effects and multiplicative interaction (AMMI), and Genotype plus Genotype by Environment (GGE) biplot, effectively clarified hybrid performance and adaptation. Moreover, the applied analyses separated broadly adapted high performers and poorly adapted hybrids. Overall, the results displayed that breeding for maize production should prioritize hybrids that tolerate high planting densities and maintain stable yield across locations.

### Author contribution

Conceptualization: M.A.A.H.G., M.I.A., N.Q., R.M.A., T.A.E.A., E.M. Methodology: M.A.A.H.G., M.I.A., N.Q., R.M.A., T.A.E.A., E.M. Software: M.O.A., F.A.S., N.M.A. Validation: M.O.A., F.A.S., N.M.A. Formal analysis: M.O.A., F.A.S., N.M.A. Investigation: M.A.A.H.G., M.I.A., N.Q., R.M.A., T.A.E.A., M.O.A., F.A.S., N.M.A., E.M. Resources: M.O.A., F.A.S., N.M.A. Data curation: M.O.A., F.A.S., N.M.A. Writing-original draft: M.O.A., F.A.S., N.M.A. Writing-review & editing: T.A.E.A., E.M. Visualization: M.O.A., F.A.S., N.M.A. Supervision: T.A.E.A., E.M. Project administration: T.A.E.A., E.M. Funding acquisition: M.O.A., F.A.S., N.M.A. All co-authors reviewed the final version and approved the manuscript before submission.

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